Galaxy Formation: A Theorist's Review

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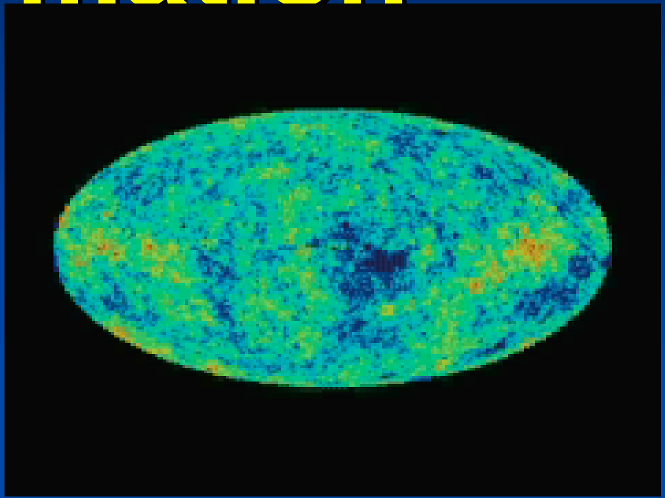
Basic Problem of Galaxy Formation

- How do we turn this at $z \approx 1089$ ($\delta \sim 10^{-6}$)…



WMAP Tem
Fluctuations

- into this at $z \approx 0$ ($\delta \sim 10^{6+}$)?

GO
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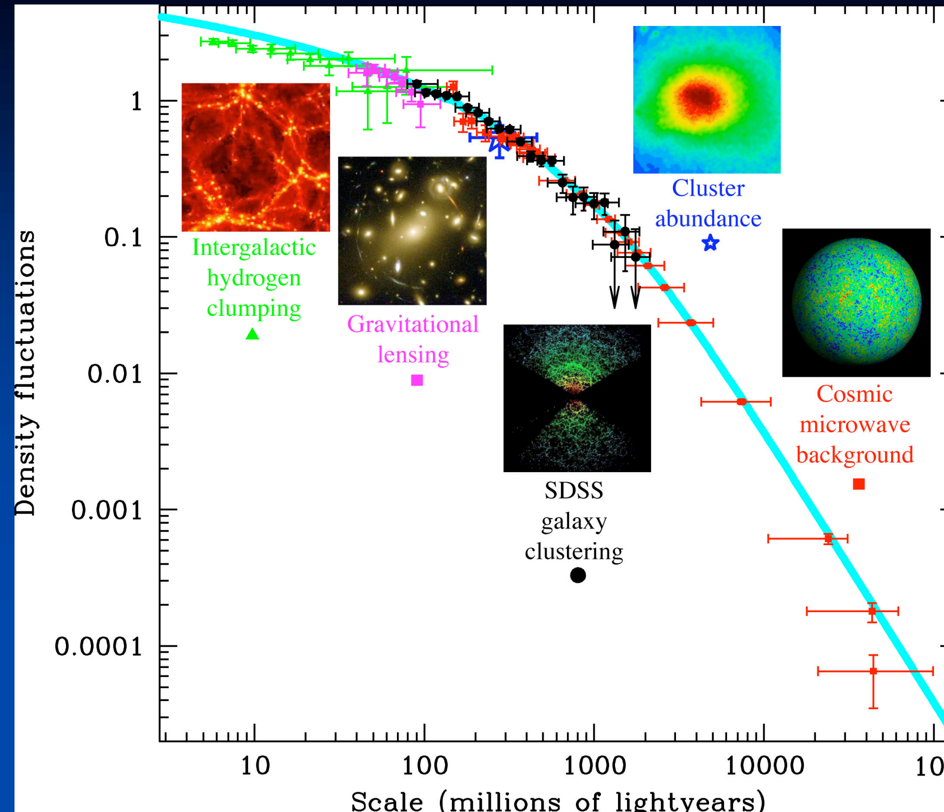
- We have a *very* successful theory for large-scale structure formation in hand with ΛCDM.
- *How do galaxies form inside large-scale*

Concordance Model

- ΛCDM with $\Omega_m \approx 0.3$, $\Omega_\Lambda \approx 0.7$, $H_0 \approx 70$ km/s/Mpc, $n \approx 1$: Works over a wide range of scales, for wide range of observations.



From Max T...

- $\Omega_b \approx 0.04$ (baryon density):
  - [D/H] + BBN: $\Omega_b \approx 0.019h^{-2}$ (cf. Kris Sigurdsson's talk).
  - CMB: Height of first peak relative to second gives $\Omega_b \approx 0.024h^{-2}$.
  - Lyα forest: $\tau \propto \rho^2/\Gamma_{HI}$, measure $<\tau_{HI}>$, $\Gamma_{HI} \Rightarrow \Omega_b^2$.

- We have the framework within which to study

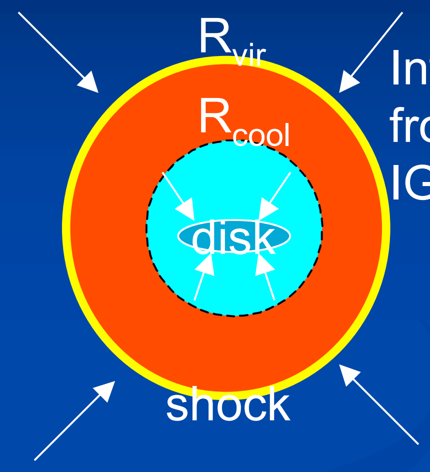
Theory vs. Observations

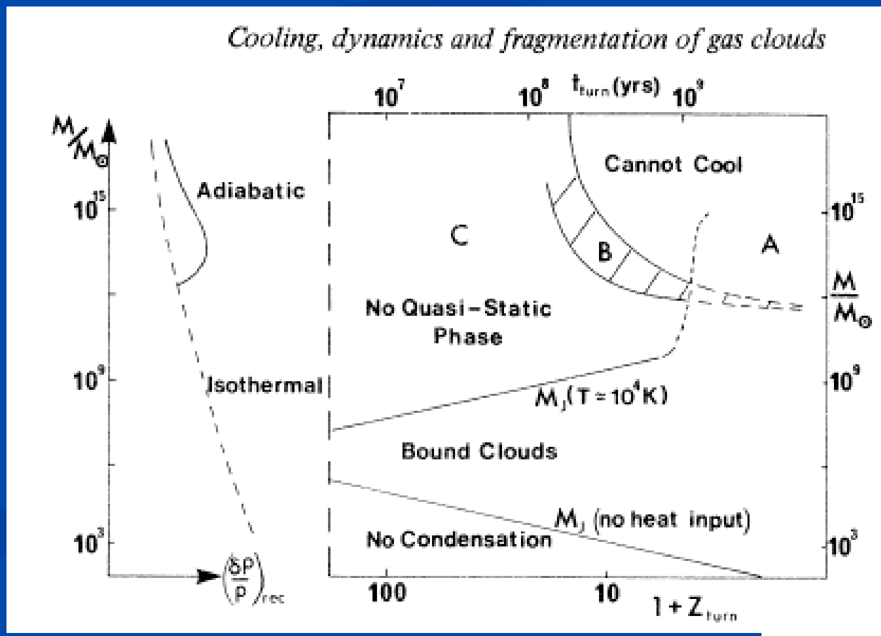
A successful theory of galaxy formation must self-consistently explain a growing set of multi-wavelength data across much of cosmic time:

- Cosmic star formation history, as a function of color and mass.
- Luminosity functions of galaxies, from UV to NIR, from z~0_5+.
- Clustering of galaxies and properties as a function of environment.
- The Hubble sequence, its establishment and evolution.
- Color-magnitude diagrams showing red sequence and blue cloud.
- X-Ray observations of excess entropy in clusters & groups.
- Sub-mm/FIR sources and the amount of dust-enshrouded SF.
- Quasar spectra showing IGM metals that must originate in galaxies.
- The appearance of large central AGN, particularly at early

Modeling Galaxy Formation

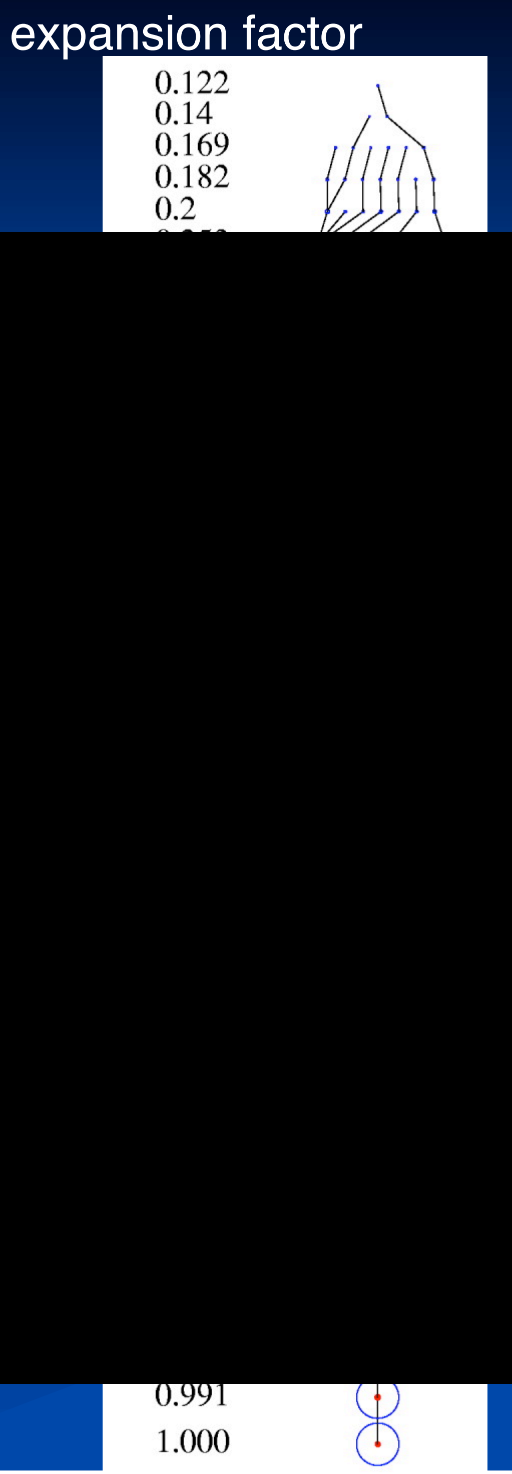
- Analytic (70's): White&Rees: Dark halo growth+baryonic cooling ⇒ galaxies. Rees&Ostriker, Binney.
- "Semi-analytic" (Kauffmann & White 92): Press-Schecter halo population + merger trees + star formation recipe ⇒ ensemble galaxy properties.
- N-body simulations (80's): Cosmic Web. Merged with SAMs (00's).
- Hydro simulations (90's).
- Many competing highly nonlinear processes must be predicted to high precision ⇒





Rees & Ostr

Semi-Analytic Models (SAMs)



- Idea: Galaxy properties are governed by mass & merging history of halos [redacted] which they reside.
- Obtain halo merging history by [redacted] Carlo realization of EPS, or from [redacted] sims.
- Concepts: (spherical White&Re[redacted] halos)
  - Gas settles into disks, forms st[redacted]
  - Halo mergers ⇒ Galaxy merge[redacted] ⇒ burst of SF + morphology alt[redacted]
  - Feedback in various forms (eg [redacted] AGN), plus metal production.
  - Compare to data: dust reproces[redacted] stellar models, population synth[redacted]
- Each concept is described by a [redacted] parameters. Parameters are tu[redacted] match some observations @ z~[redacted]
- SAMs are fast, can make a wide[redacted] of predictions, and match obser[redacted] trends.
- However, they have MANY free

Simulating Forming Galaxies

- SAMs are cheap and easily tunable (always matches data!); N-body simulations are more expensive but reliable; Hydro sims are brutally costly an [redacted]

<u>Simulating Dark Matt</u> [redacted]

Gravity: Gm_1m_2 / r^2

<u>2005 status</u>
Largest N: 10^{10}
Dynamic Range: $3x10^5$

Simulating Forming Galaxies

- SAMs are cheap and easily tunable (always matches data!); N-body simulations are more expensive but reliable; Hydro sims are brutally costly and painfully inaccurate!

Simulating Dark Matter

Gravity: Gm_1m_2 / r^2

Simulating Baryons

Gravity: Gm_1m_2 / r^2

Pressure: $-\nabla P/\rho$

Shocks: Viscosity

Cooling: $\Lambda(\rho,T)$

Photoionization: $J_\nu(\mathbf{r},T,\rho)$

Heuristic star formation

Supernova feedback/winds

Heavy element production

Active Galactic Nuclei

Magnetic fields…

2005 status

Largest N: 2×10^8

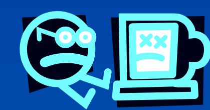
Dynamic Range: 5×10^4

Elements of Galaxy Formation Theory

- How does gas get *into* galaxies?

  - CDM + shock heating + cooling

    $\Rightarrow$ Classic overcooling problem



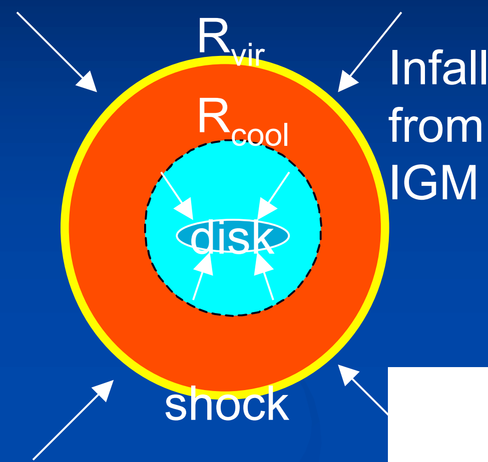
- How does gas get *out* of galaxies?

  - Feedback, winds, AGN, jets, etc.

- *Bottom line:* Lots of understanding and progress on the former, little understanding of the latter.

How Gas Gets Into Galaxies

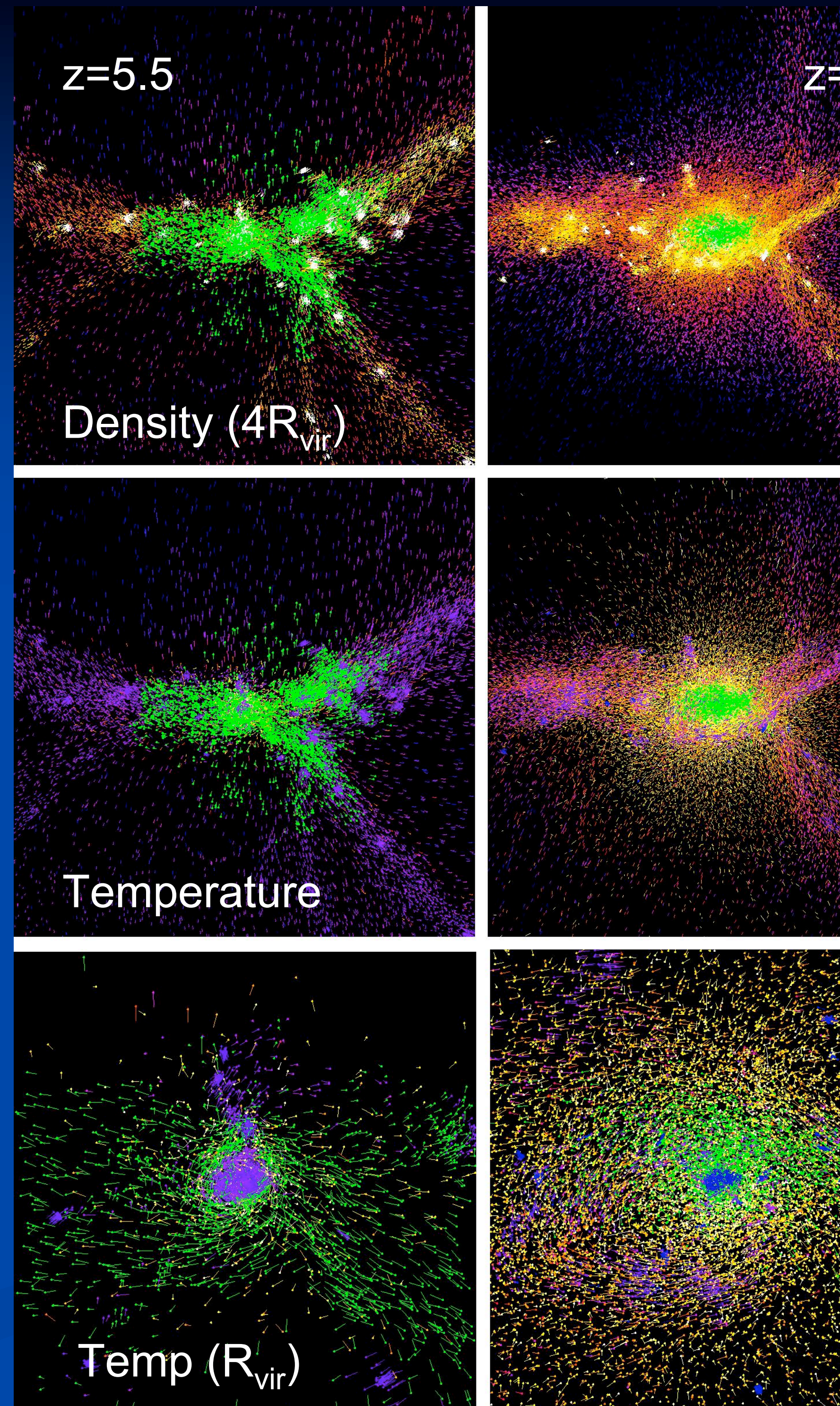
- Modes of Gas Accretion (Keres et al 05):
  - Hot Mode: (White&Rees 78) Gas shock heats at halo's virial radius up to T_{vir}, cools slowly onto disk. Limited by t_{cool}.
  - Cold Mode: (Binney 77) Gas radiates its potential energy away in line emission at $T \ll T_{vir}$, and never approaches virial temperature. Limited b[redacted]



- Cold mode dominates [redacted] in small systems ($M_{vir} < 3\times10^{11} M_\odot$), and thus at early times.

Accretion in a Growing Halo

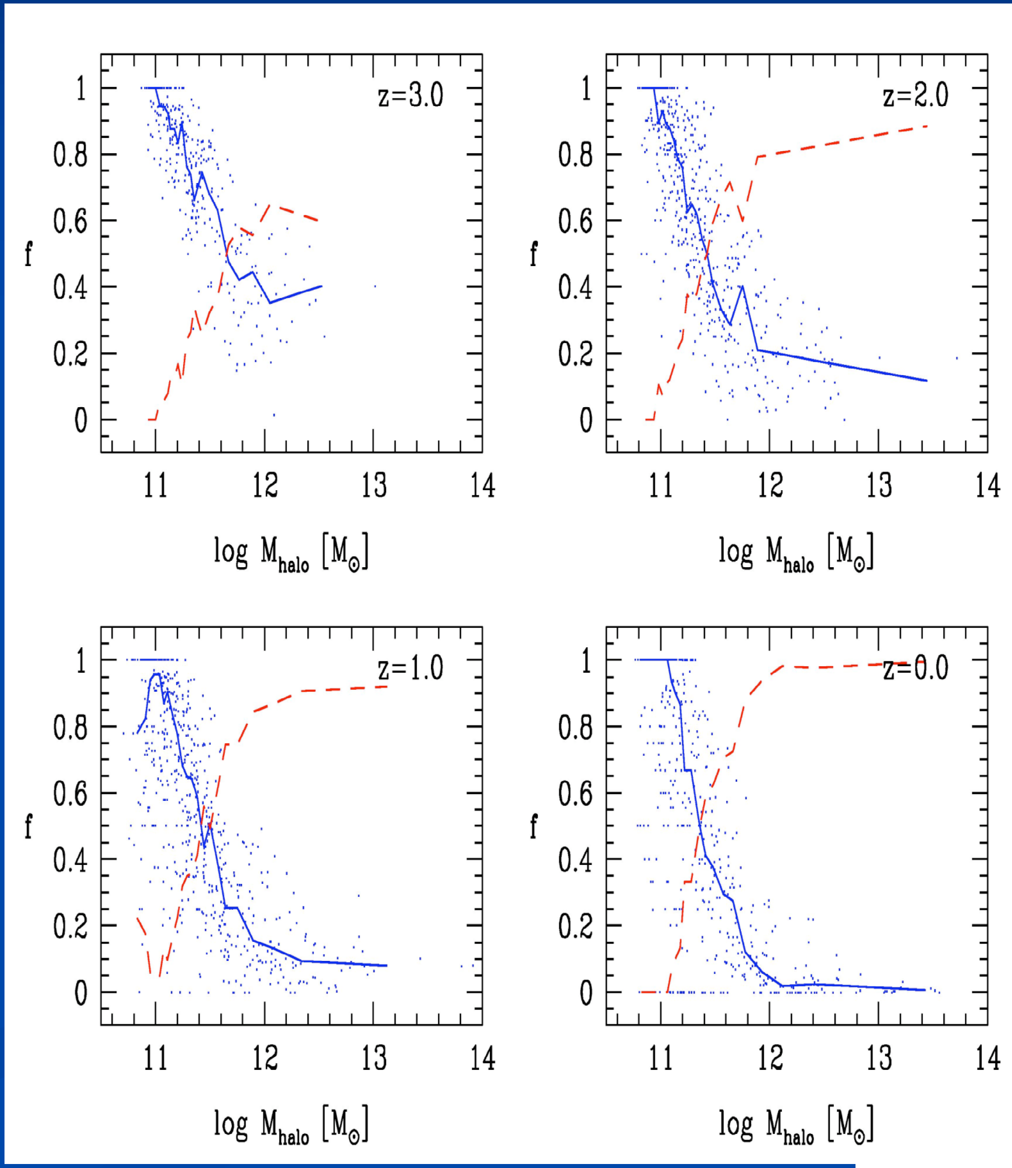
- Left panels: z=5.5, right panels: z=3.2.
- Halo grows from $M \sim 10^{11} M_{\odot}$_$10^{12} M_{\odot}$, changes from cold _ hot mode dominated.
- Left shows cold mode gas as green; Right shows hot mode as green.
- Cold mode filamentary, extends beyond R_{vir}; hot mode quasi-spherical within R_{vir}. Filamentarity enhances



Global Accretion in Hot & Cold Modes

Keres et al 2005

- Accretion rate shows two distinct modes, based on maximum temperature reached by gas.
- Cold mode dominates at z>2. At z~3, 95% of gas has never reached T_{vir} before forming into stars.
- Global $T_{thresh} \approx 2.5 \times 10^5$K.
- Clearest separation in halo mass, with dividing mass of $\sim 10^{11.4} M_{\odot}$ (depends on Ω_b/Ω_m).
- Results confirmed in 1-D models of galaxy growth (Birnboim & Dekel 2003)



Analytic Analysis of Shock Stability

- Birnboim & Dekel (2003): Shocks near virial radius are unstable to radiative cooling for $M_{halo} < \text{few} \times 10^{11} M_{\odot}$.
- In this 1-D model of cosmological halo growth, virial shock is not formed until this L_* halo has accreted the bulk of its mass, after z~2.
- Similar threshold is seen using Gadget-2; qualitatively similar behavior in AMR.

8 *Y. Birnboim & A. Dekel*

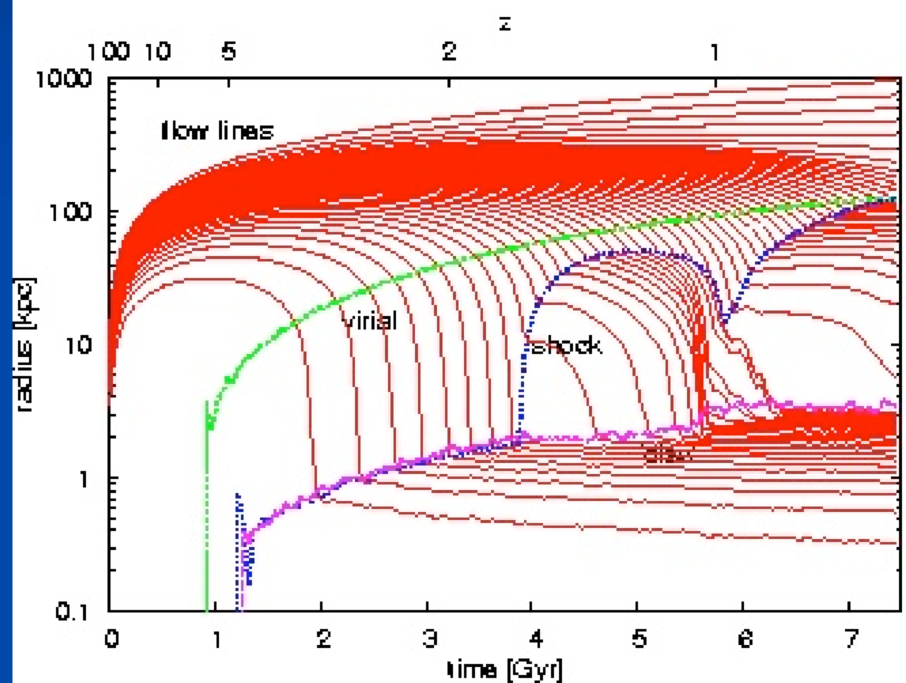
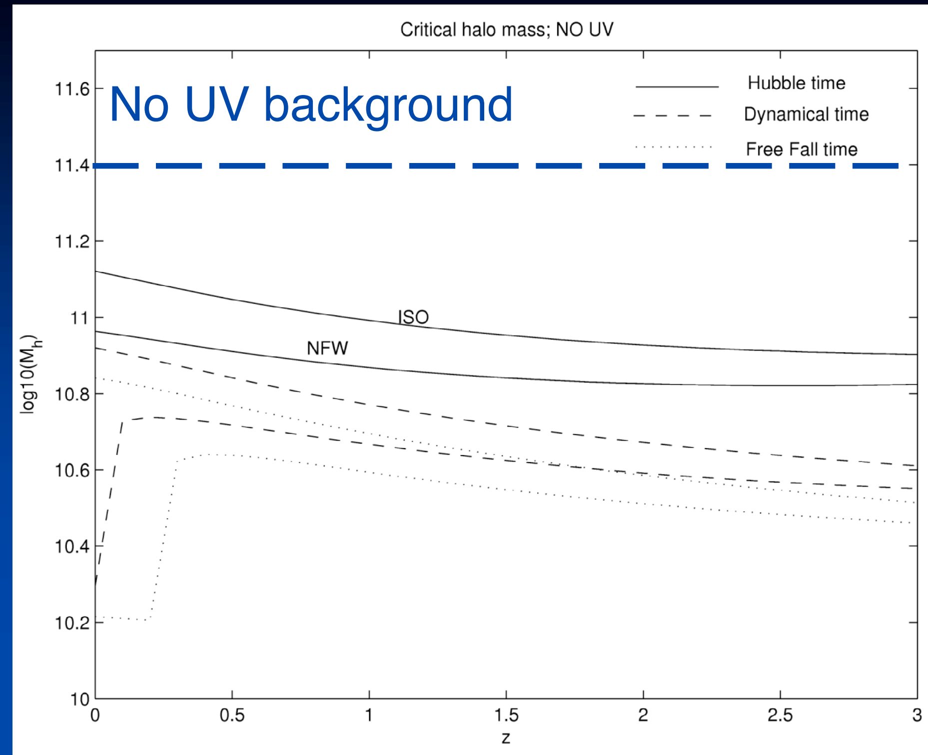
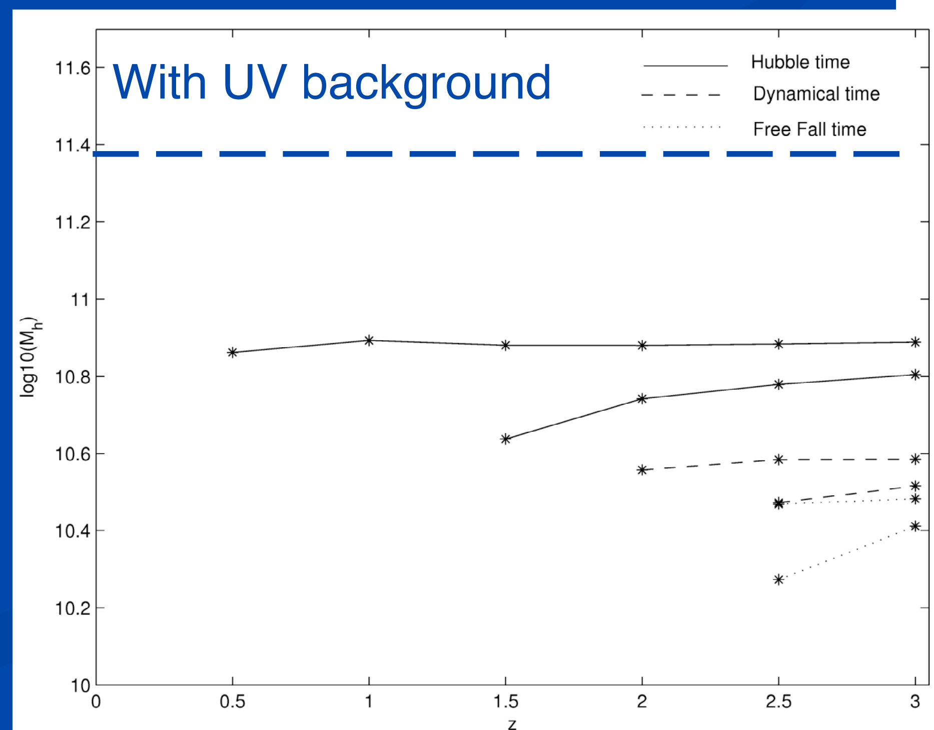


Figure 3. Simulation of the *radiative cooling* case, with $Z = 0$. The curves are as in Fig. 2, with the 'disc' radius added. There is no shock outside the 'disc' at early times, when the virial mass is small, because the cooling is too efficient. A shock develops at later times, when the mass is larger, and it quickly propagates outwards. After a couple of oscillations the shock radius approaches the virial radius.

Threshold Mass: Sims vs. SAMs

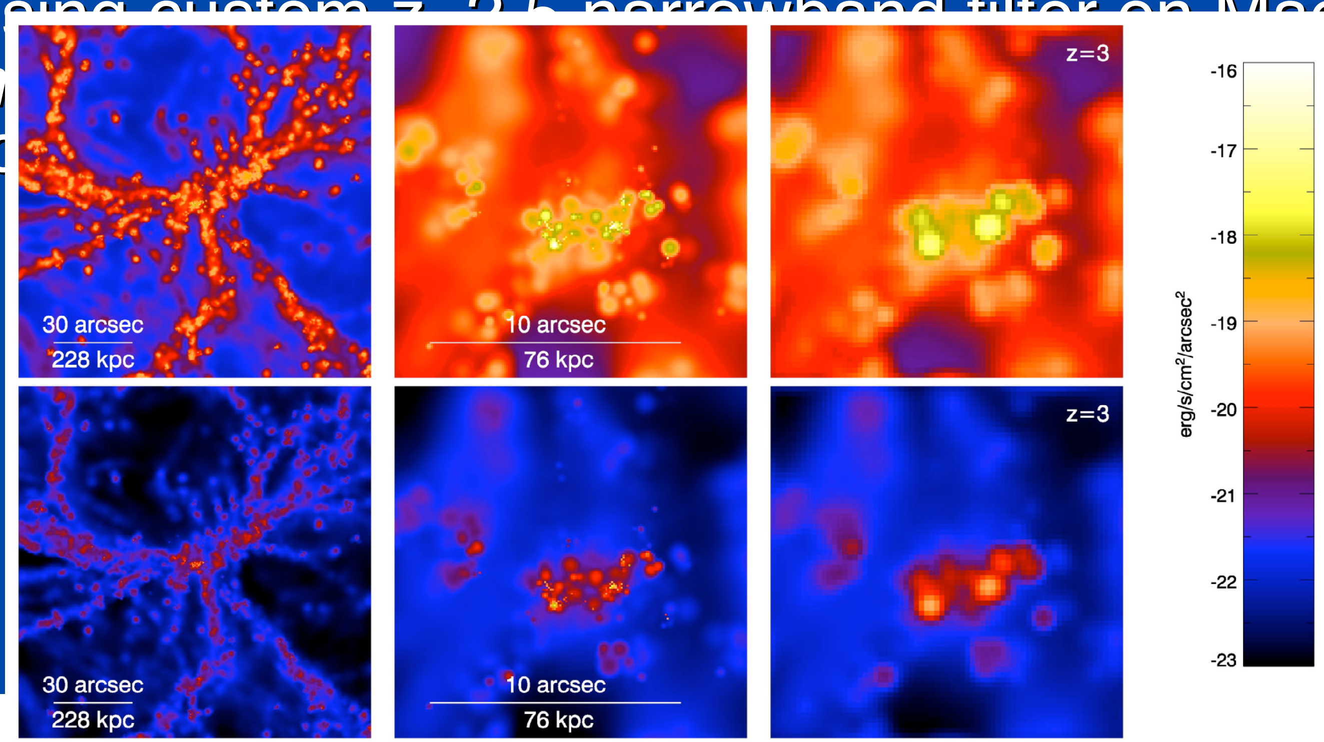
- Threshold mass for hot accretion: $M_{halo} \approx 10^{11.4} M_{\odot}$.
- Cooling time arguments alone (Frenk & White 91) typically used in SAMs give somewhat lower threshold mass.
- To get stable virial shock, need both long cooling time and interior pressure support (grown from central galaxy).





Detecting Cold Accretion

- Potential energy of infalling gas emitted in HI and HeII lines.
- Should be detectable as faint Lyα blobs around high-z galaxies.
- Many blobs (~40) seen by Matsuda et al 2004; largest (Steidel's & Dey's) likely fueled by outflows/AGN, but most exceed E_{SF}.
- We are obtaining imaging spectroscopy of Lyα blobs in CDF-S using custom z~2.5 narrowband filter on Magellan (first *blin*... ...ollow-up as disc...



Yang et al 200
Simulated Lya
(top) and HeII
emission maps

Major Merging vs. Smooth Accretion

- *Halos* grow by merging, but in general *galaxies* don't!
- Jeans mass for baryons is large (compared to dark matter), so gas gets "smoothed" prior to falling into galaxy.
- Galaxies get most of their mass by smooth accretion or minor mergers, *not* major mergers.
- Minor mergers contribute little at lower redshifts.
- Globally, SFR follows smooth accretion rate.
- Merger rates agree with CNOC; now comparing to

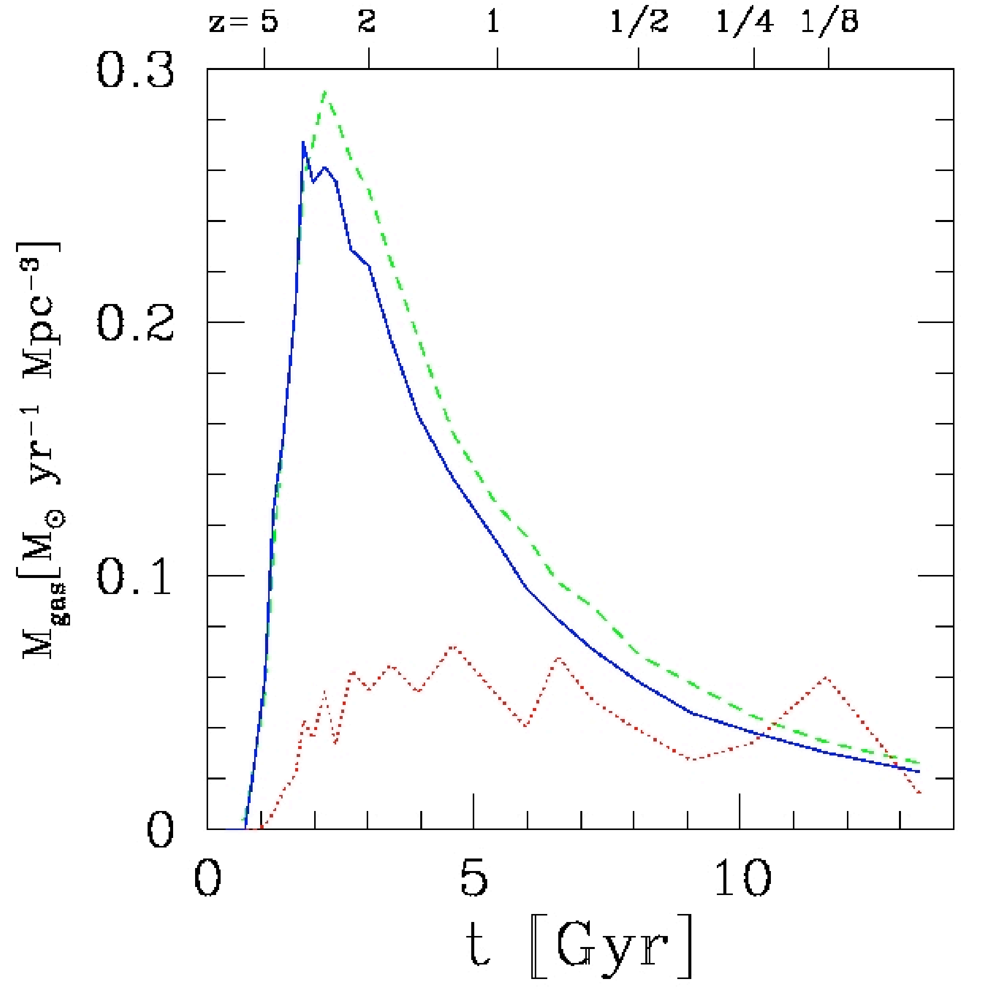


Fig. 14. Star formation rate per unit volume (dashed line) for all resolved galaxies in the simulation compared to smooth gas accretion (solid line) and merger accretion rates (dotted line). The merger mass accretion rates include the accretion of stars.

Summary: From Analytic to Simulations

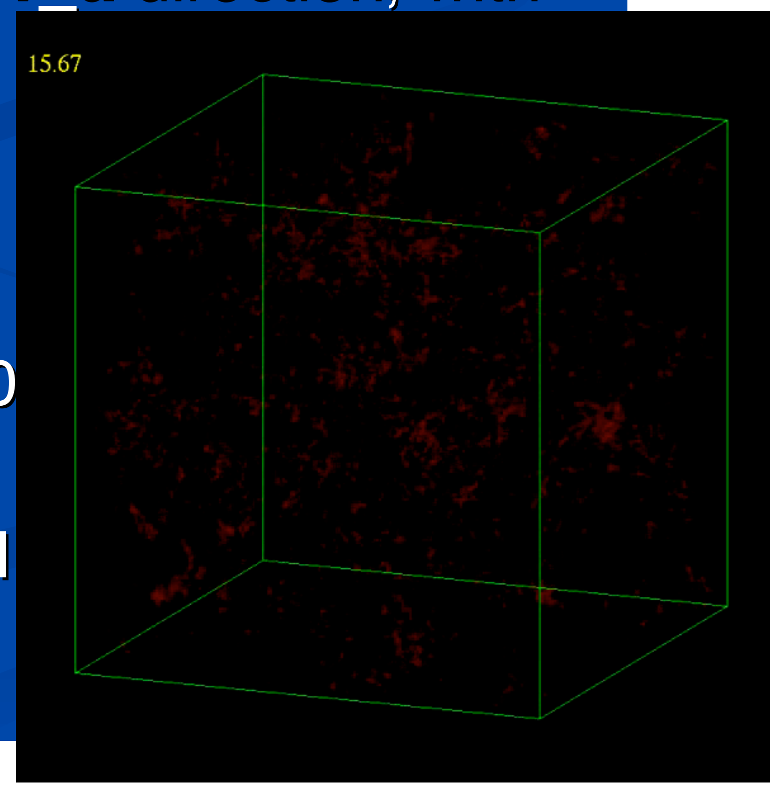
- Galaxy formation theory has a long history, invariably lagging behind (equally rapidly-improving) observations.
- Early analytic models (70's) provided framework for understanding basic properties of galaxies.
- These models were built upon by SAMs, adding a host of parameters to match observational properties in a simple (and fast) framework.
- Simulations capture the full dynamics of gas accretion, but limited by CPU time, resolution, and volume. Also, they still need heuristic prescriptions (like SAMs) for subgrid processes.
- Simulations have provided interesting modifications to the standard analytic lore of galaxy formation, including the importance of "cold mode" and fundamental differences in the behavior of baryons compared to the dark matter.

Galaxy Formation Sims: Status Report

- Fundamental predictions:
  - Plenty of early, massive galaxies; plenty of early star formation.
  - Big galaxies form stars fast & early in small units, then *dry merge*.
  - Early galaxies are highly biased and clustered; reduces with time.
- Predictions that seem to disagree with observations:
  - Overcooling: Without feedback, too many stars form.
  - Luminosity function: Too many bright galaxies, faint steep end.
  - Angular momentum problem: Can't form Sc/d galaxies

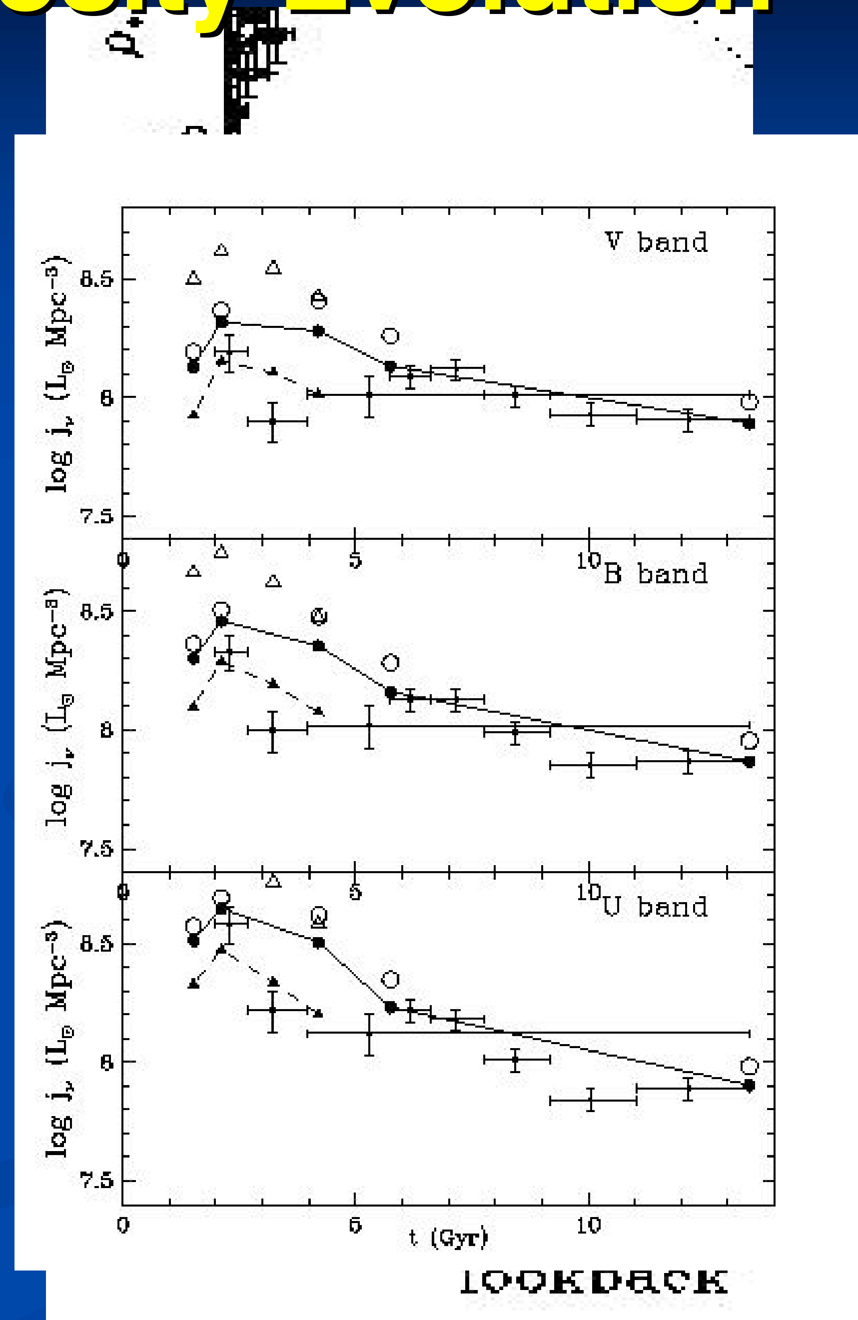
Gadget-2 Hydro Simulations

- Entropy-conservative SPH + Tree-PM (Springel & Hernquist).
- H&He cooling, J_ν (uniform), star formation matching Kennicut Law.
- Multi-phase subgrid ISM model, based on McKee & Ostriker.
- Thermal feedback (added to hot ISM) and superwind feedback (expels gas from galaxies in **v_a** direction, with v_{wind}~500 km/s).
- A state of the art simulation:
  - $2x486^3$ particles: $m_{SPH}=1.3x10^8\ M_\odot$.
  - L=100 Mpc/h, ε=5 kpc/h.
  - ΛCDM: Ω=0.3, h=0.7, σ_8=0.9, Ω_b=0.0
- Recent additions:
  - Metal cooling: adds 30-50% to global
  - Momentum-driven winds: $v_{wind} \propto \sigma_{gal}$.
  - Type Ia supernovae enrichment.



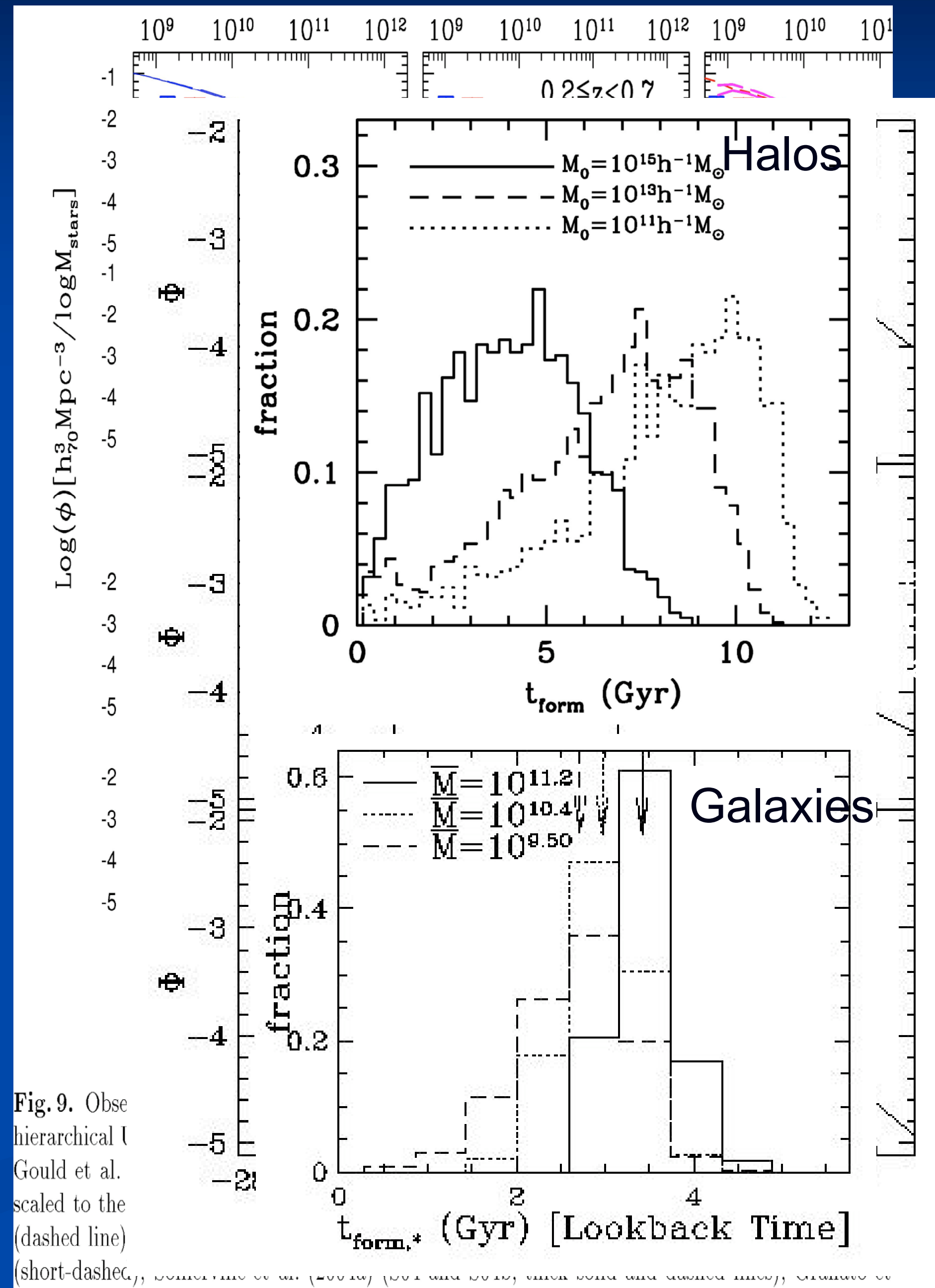
Global SFR & Luminosity Evolution

- Cosmic SFH agrees reasonably well, with a peak at z>5. Perhaps too much early SF? Data uncertain.
- Rudnick et al (2004): SDSS + Combo-17 + FIRES, selecting massive galaxies to z~3.
- Simulations show that universe was brighter in past in U and (less so) in V, by roughly the observed factors.
- Kristian (after coffee) will show more detailed comparisons at z~4.
- Overall broad agreement in evolution of stellar mass and SFR in massive galaxies.



Massive Galaxy Evolution

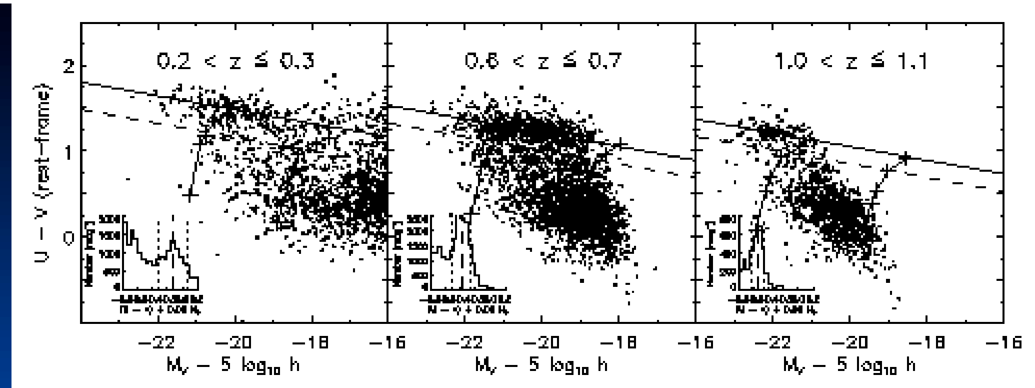
- NIR Surveys: Massive galaxies are in place at z~2 ⇒Early epoch of stellar mass growth in the Universe.
- Number densities seen in e.g. K20 to z~2 agrees with models: Big galaxies form stars early, then "dry merge".
- Downsizing is a natural consequence of galaxy formation processes (i.e. it is *hierarchicial*, not *anti-hierarchical*!). High-σ perturbations collapse first, start forming stars, then get too hot and reduce their birthrate ⇒ Stellar ages inversely correlated with halo

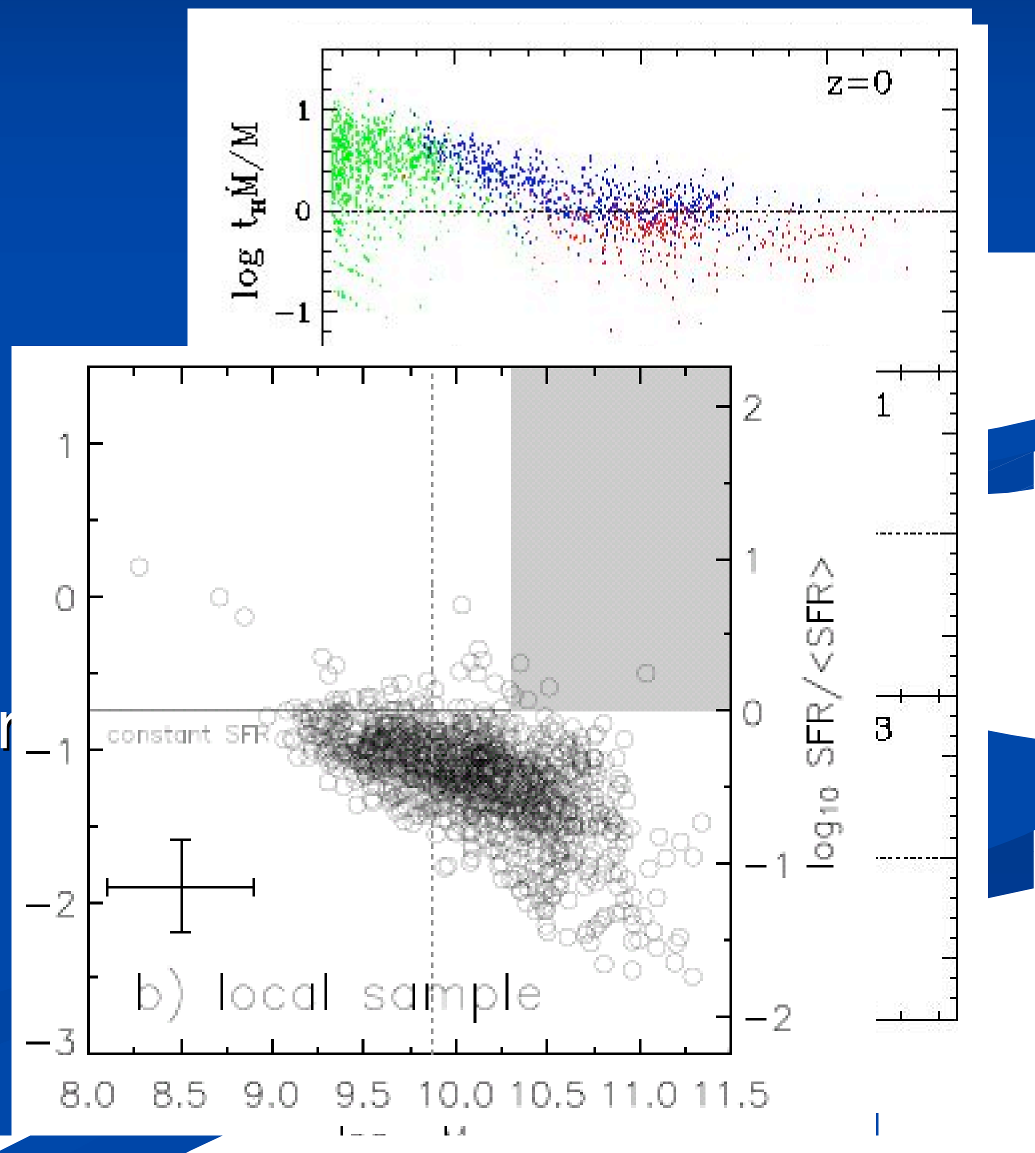


Bell et al 2003

No Red & Deads!

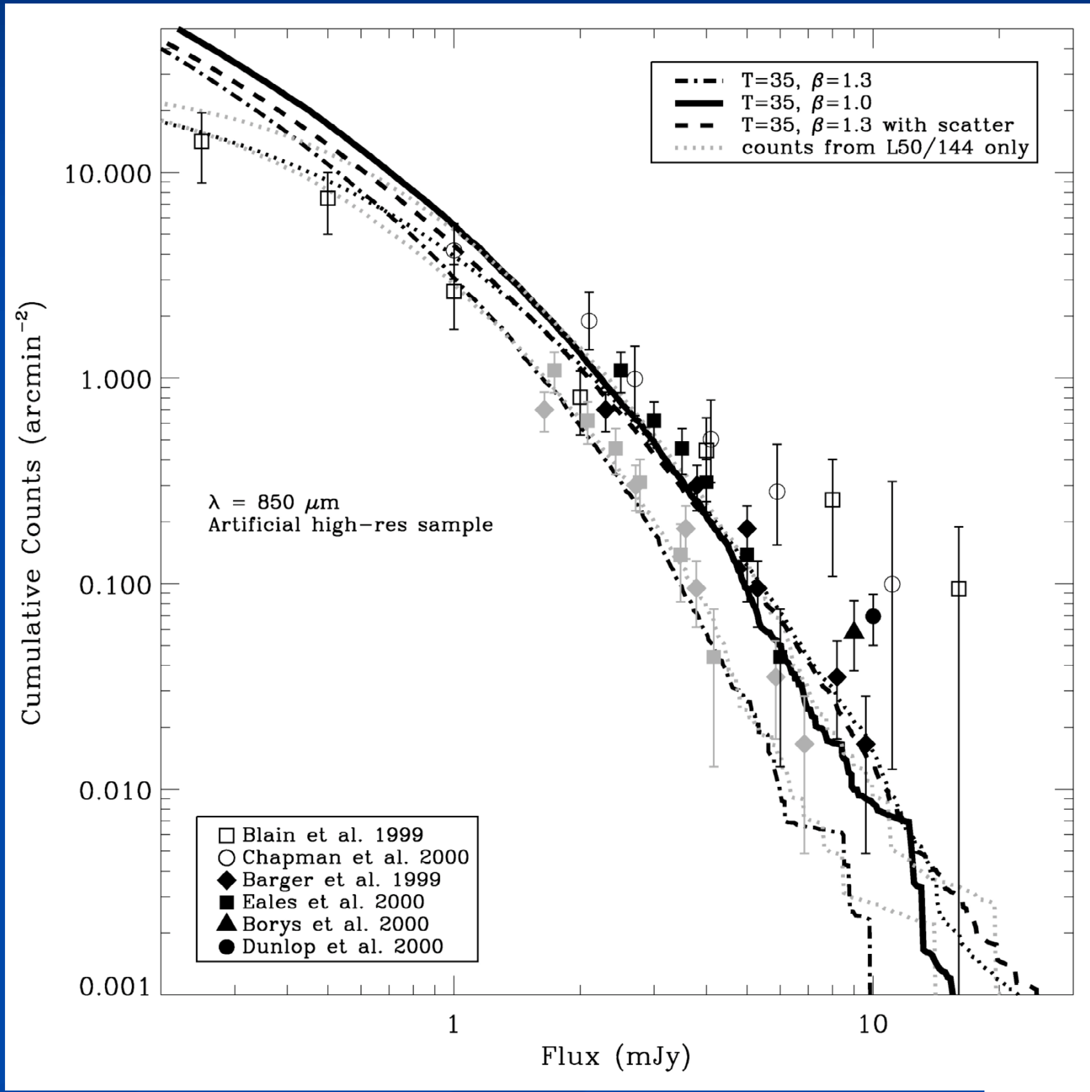
- Clusters & field ellipticals lie along red sequence, at U-V≈1.5, with brighter galaxies redder.
- Simulations show no red sequence, no trend with M_V.
- Truncate SF in galaxies with $M_* > 2 \times 10^{10} M_\odot$: No blue cloud, no gap! (M_*-Z relation included).
- Eliminate hot mode accretion: More blue cloud objects, but odd looking red sequence/color gap.
- Truncating SF on bulge mass in SAMs seems to work OK (Somerville etal).
- What causes truncation (AGN)? Transition objects





SCUBA sources and ERO's

- Lots of bright sub-mm galaxies at z>2, with SFR~1000 $M_\odot$/yr.
- Using simulated SFR_F_{850} (for various dust models) yields deficit at bright end… need to check with updated models!
- Possibly related: Enough ERO's/ DRG's at z~2? Need E(B-V)~0.4 (Nagamine et al).
- Lack of merger-induced bursts? How do SCUBA sources relate to ERO's, LBGs and



Fardal et al.

X-Ray Scaling Relations

- Scaling relations depart from “self-similar” ⇒ increased entropy in smaller systems (lower L_X).
- Simulations in broad agreement with trends (but tantalizingly low), in both inner and outer regions.
- Trend produced by increased efficiency of galaxy formation in smaller systems (Bryan & Voit).
- SN feedback prevents overcooling, but mild effect on scaling relations.
- Kay etal: Add lots of S to 10% of cluster gas, can match relations.
- Is non-gravitational heating needed to match scaling relations? If so, when? What is

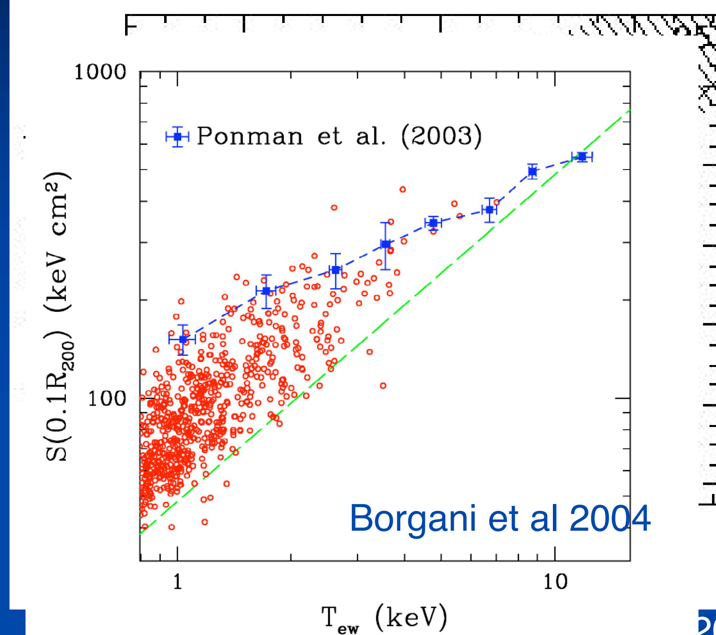
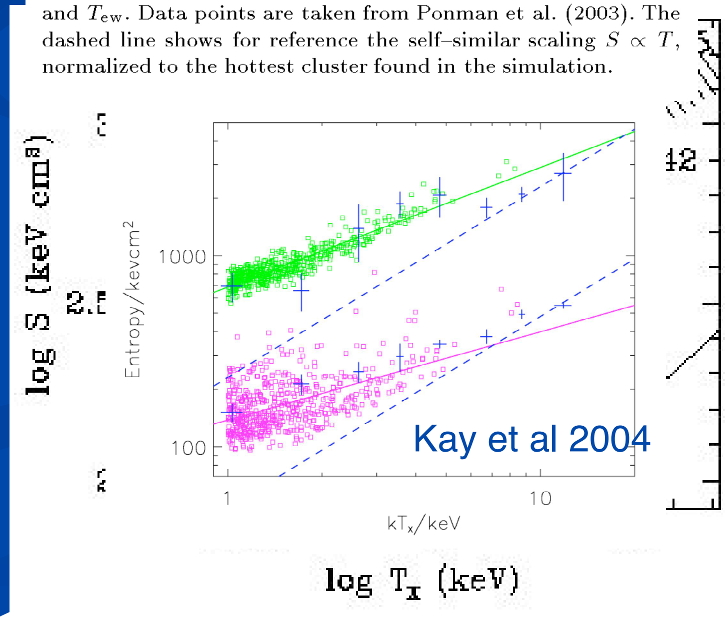
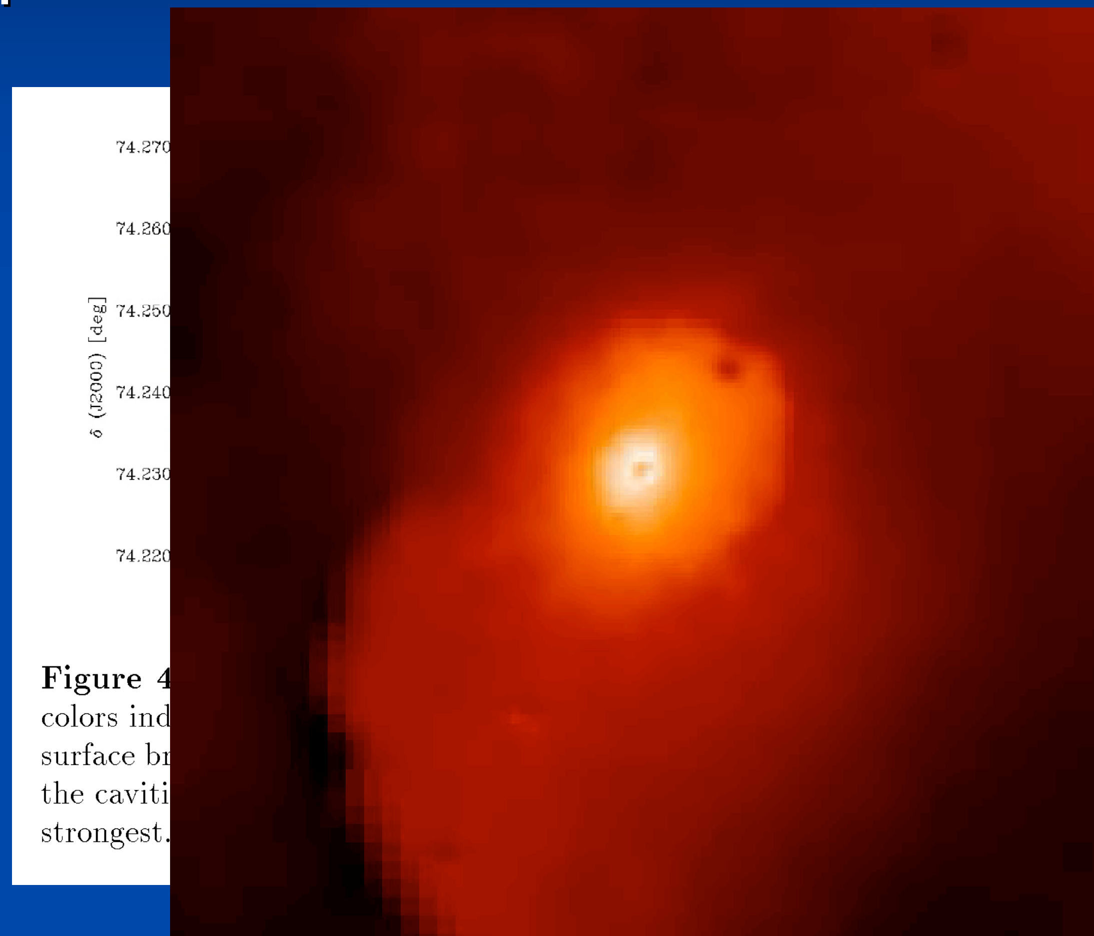


Figure 14. The relation between gas entropy computed at $0.1\,r_{\rm vir}$ and $T_{\rm ew}$. Data points are taken from Ponman et al. (2003). The dashed line shows for reference the self–similar scaling $S \propto T$, normalized to the hottest cluster found in the simulation.



Cluster Bubbles: Smoking Gun?

- Cooling flows not seen in accord with expectations: Need central heat source.
- “Bubbles” seen in radio & X-ray maps contain hot, tenuous gas. Adding ~1/3 keV/bary to ICM.
- Intermittent AGN heating can prevent cooling flows (Ruzskowski etal).
- How much energy does this add to ICM?



Ruzskowski, Begelman, E

Simulating AGN Feedback

- Di Matteo, Springel, Hernquist, etal: Couple AGN heat to gas based on Eddington accretion rate in (unresolved) central region.
- Forms AGN that satisfy M_{BH}-σ slope, and truncate SF rapidly.
- Realistic? Hmm, well… the thing is, something like this *must* happe[redacted]

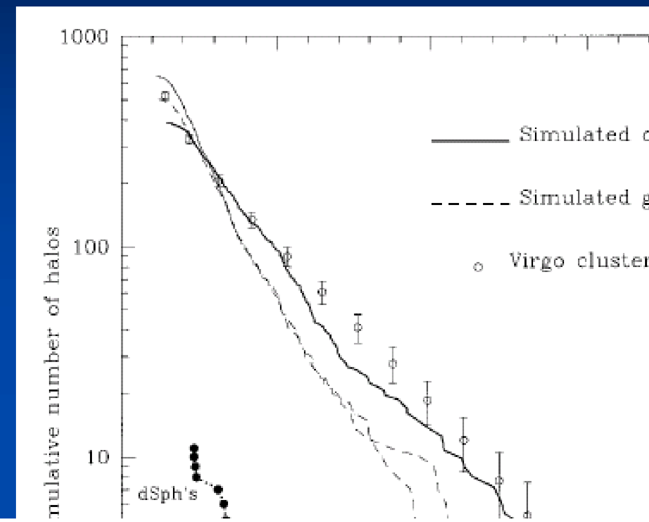
CDM on Small (galactic) Scales: Trouble?

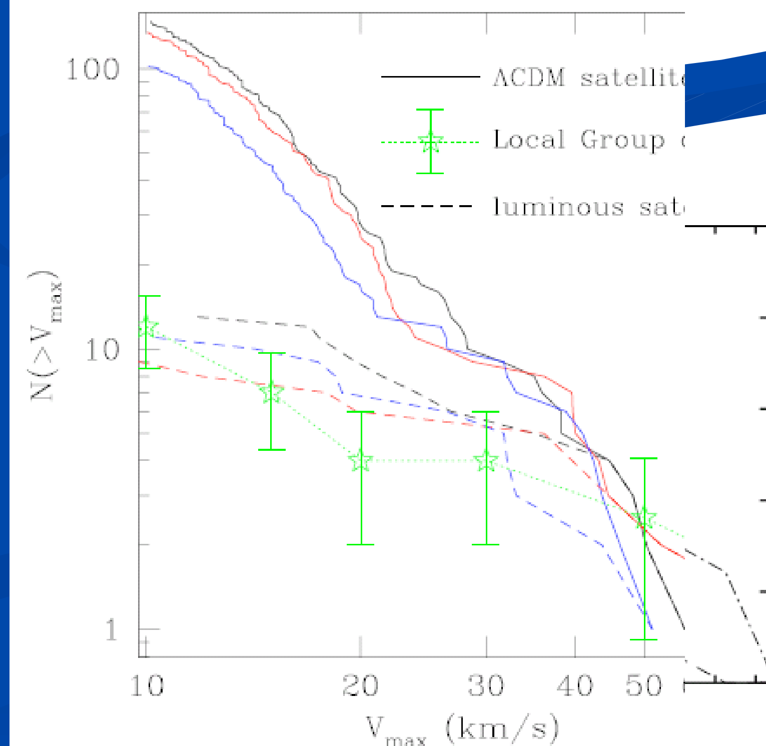
- ``Cusp problem": CDM predicts cuspy halos, observations of LSBs show cores.

$$\rho(r) = \frac{\rho_0}{(r/r_c)^{\alpha}(1+(r/r_c)^{3-\alpha})}$$

  - NFW (α=1), Moore etal ($\alpha \approx$1.5)
  - BUT… Observations very hard, most systematics push towards cores, so unclear if problem real.
  - Modified DM? Self-interacting, decaying, annihilating, fuzzy, ...
- ``Substructure problem": CDM predicts self-similar halos, observations shows clusters have MANY more subhalos than galaxies like Milky Way.
  - Moore etal 99 shows 2 orders of mag discrepancy. CDM_ΛCDM + more satellites found reduces to 1 dex.
  - Perhaps halos are there, but stars haven't formed: reionization? Simple model works well (Kravtsov etal 01; Somerville etal 01).
  - Lensing indicates substructure in agreement with CDM, but mostly sensitive

al 2001



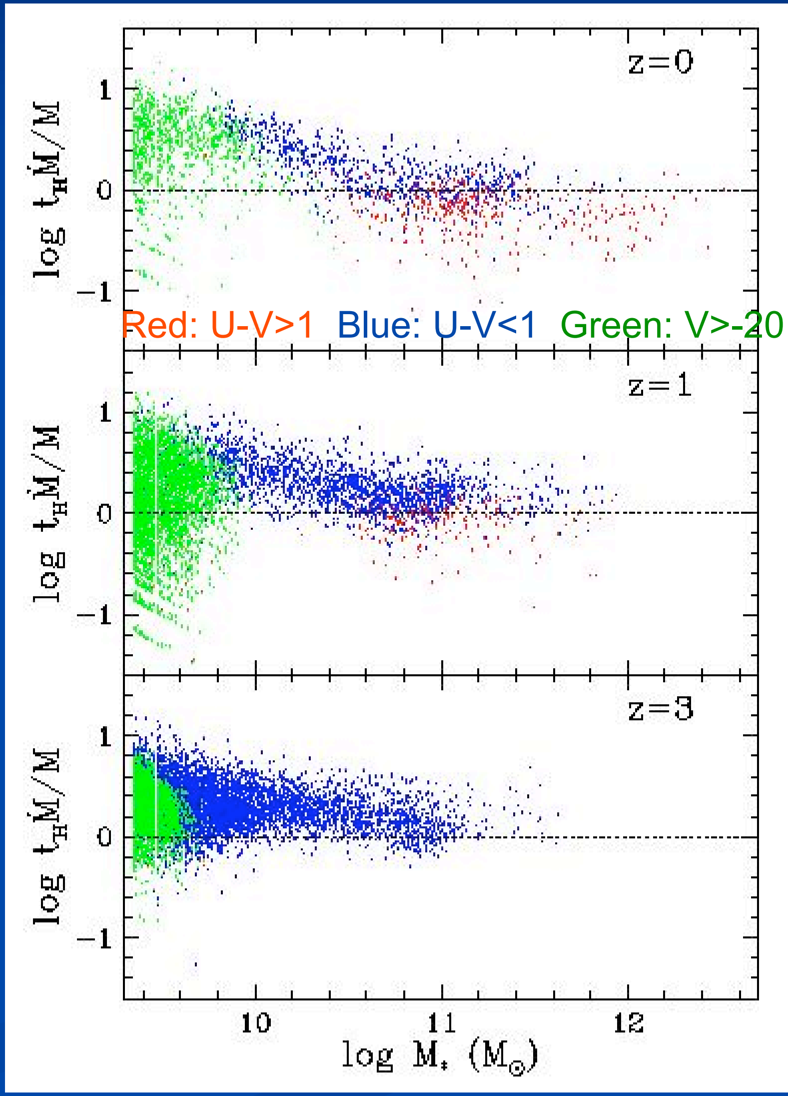


Conclusions

- We are still not quite able to simulate the observed population of galaxies arising from primordial density perturbations.
- Clustering, LSS, Lyα forest, etc, all point to ΛCDM being successful on large scales (>100 kpc). [Perhaps issues on small scales?]
- Basic predictions of current simulations:
  - Plenty of big early galaxies, due to “cold mode” path for galaxy growth.
  - Major merging is a subdominant growth mode overall, though big galaxies grow by dry merging.
  - *Trend* of downsizing is a fundamental, but *strength* is not predicted correctly.
- Simulations are able to match the cosmic star formation history, luminosity density, luminosity functions, and other properties at high redshifts (e.g. Kristian’s talk next), thanks to recent improvements.
- Feedback is the dominant issue that remains to be solved. AGN feedback offer best hope to solve a host of problems concurrently, but is it viable? Better understanding of

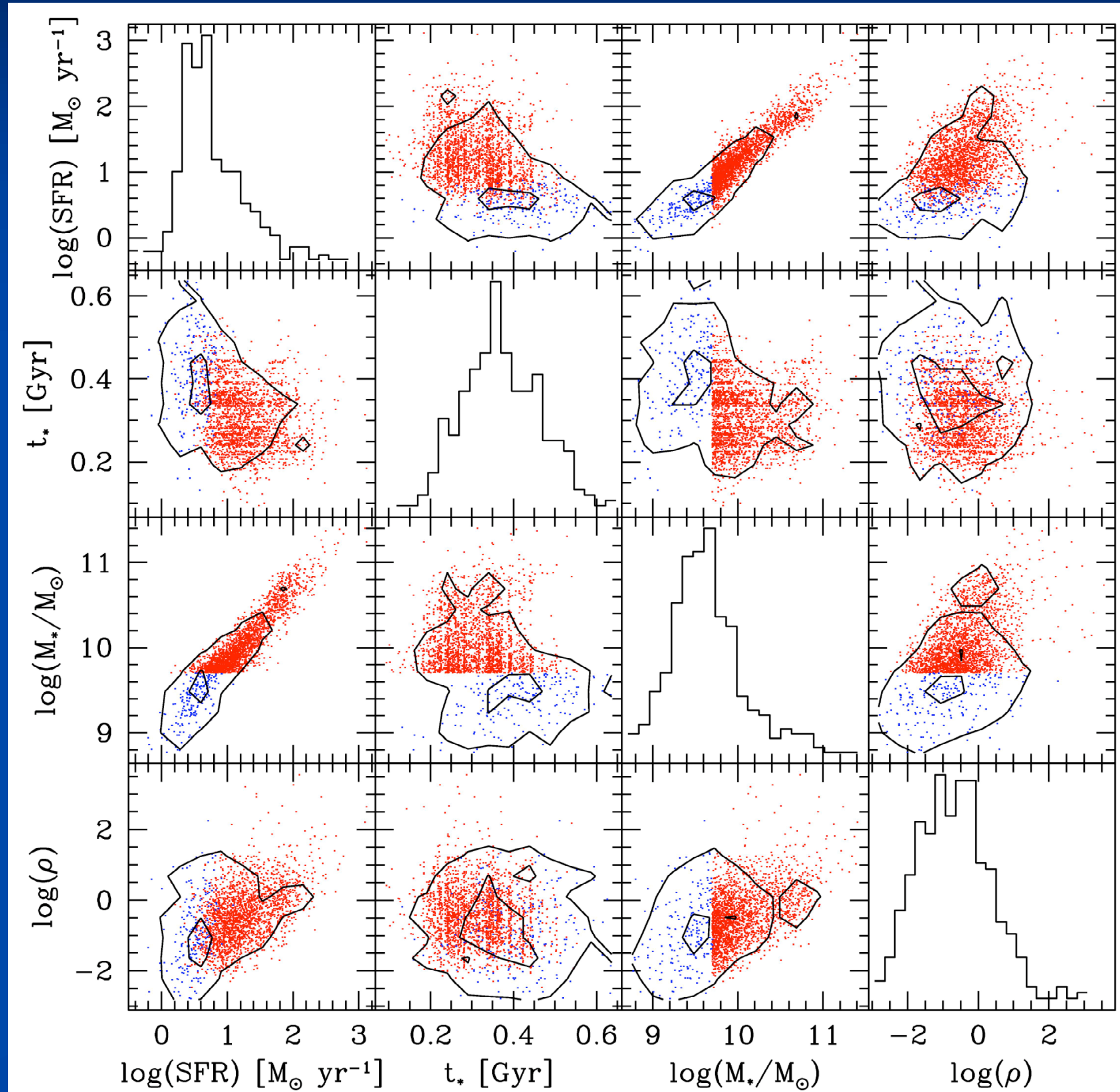
Birthrates of Simulated Galaxies

- Birthrate = t_{Hubble}xSFR/M_*
- Trend to lower birthrates in larger galaxies – GOOD.
- Massive galaxies show large birthrates at z=0 – BAD.
- Need truncated SFR in massive galaxies: AGN? (Springel etal 04)
- When are birthrates of massive galaxies truncated in real universe?



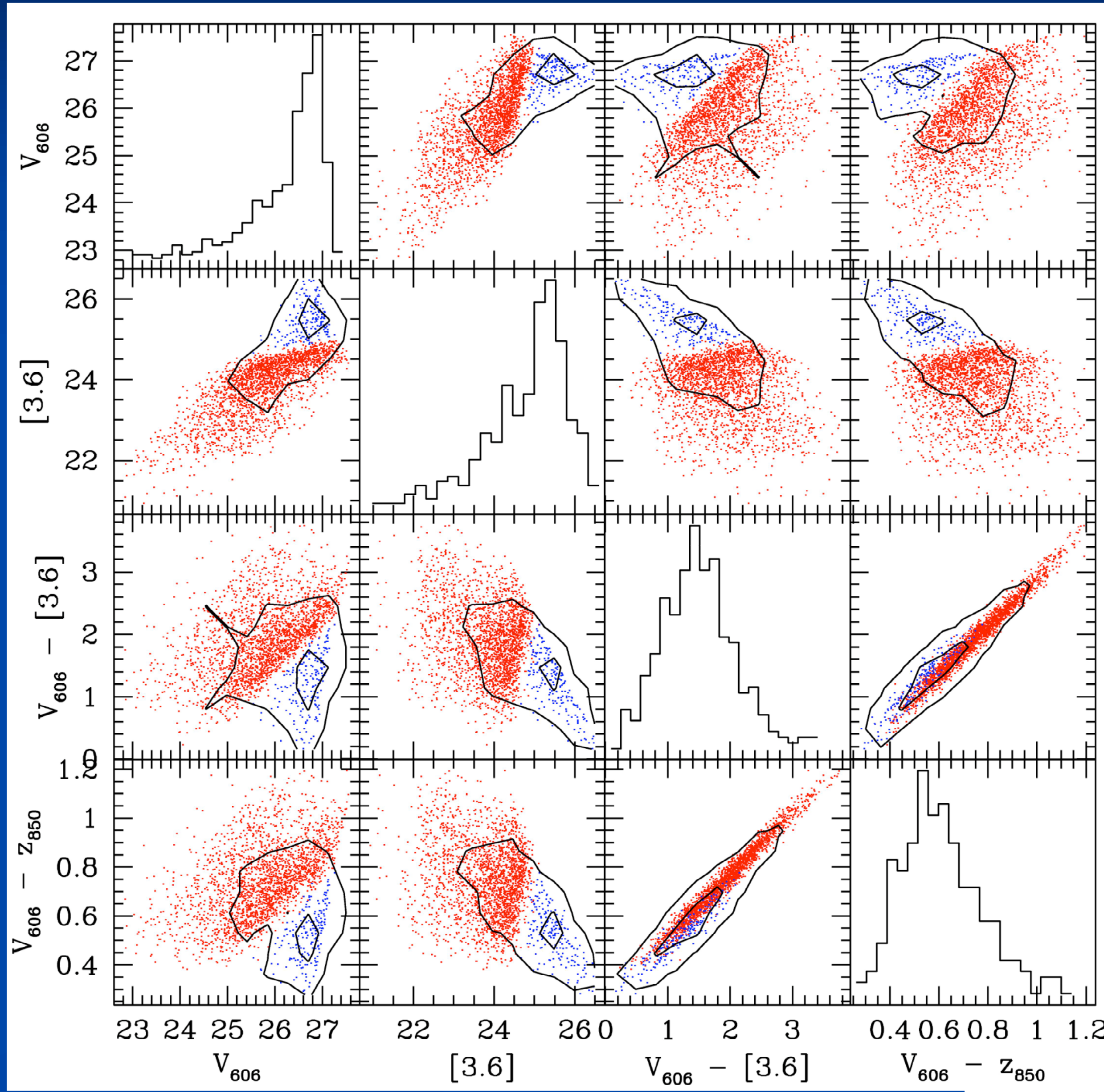
Correlations of Physical Properties

- SFR and M* closely tied: Big galaxies are forming stars fastest. Slope is ~1, so birthrates similar.
- Formation epoch loosely anti-correlated with mass: Big galaxies are older.
- Environmental dependence very weak (as seen in Bouche & Lowenthal 2005).



Correlation of Observables

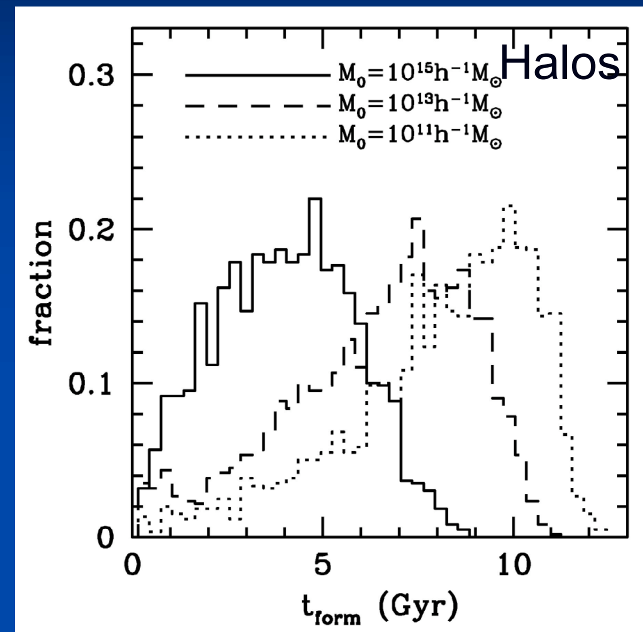
- Color-magnitude relations show scatter from dust.
- Color-color plots show tight relation: Dust scatters along line. Hey, that gives us an idea…
- Loci will be compared to GOODS data when available.

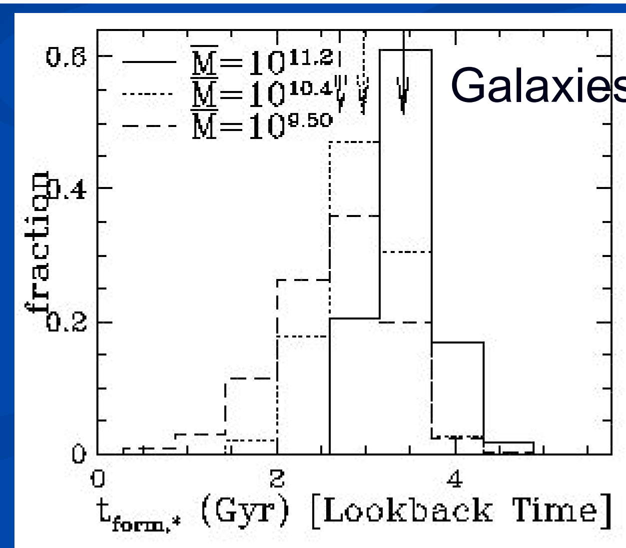


Finlator et al

Downsizing in Simulations

- Hierarchical models predict big *halos* form late, but *galaxy* formation not simply related.
- "Hierarchical" means big halos form late, but collapse early.
- Star formation begins on collapse, so halo and star formation times are anti-correlated.
- This is sometimes called "downsizing" or "anti-hierarchical" behavior, but is actually a natural prediction of CDM.
- Nevertheless, still require increased efficiency of SF at early times – happens naturally in simulations, as we shall see.





Va
Bo
etal 04

Phase Diagram of Accretion

- Operational Definition: Cold and hot mode distinguished by T_{max}, maximum temperature reached by gas until it gets into a galaxy and forms stars.
- Figure shows example phase paths of 5 particles from each case (distinction exaggerated).

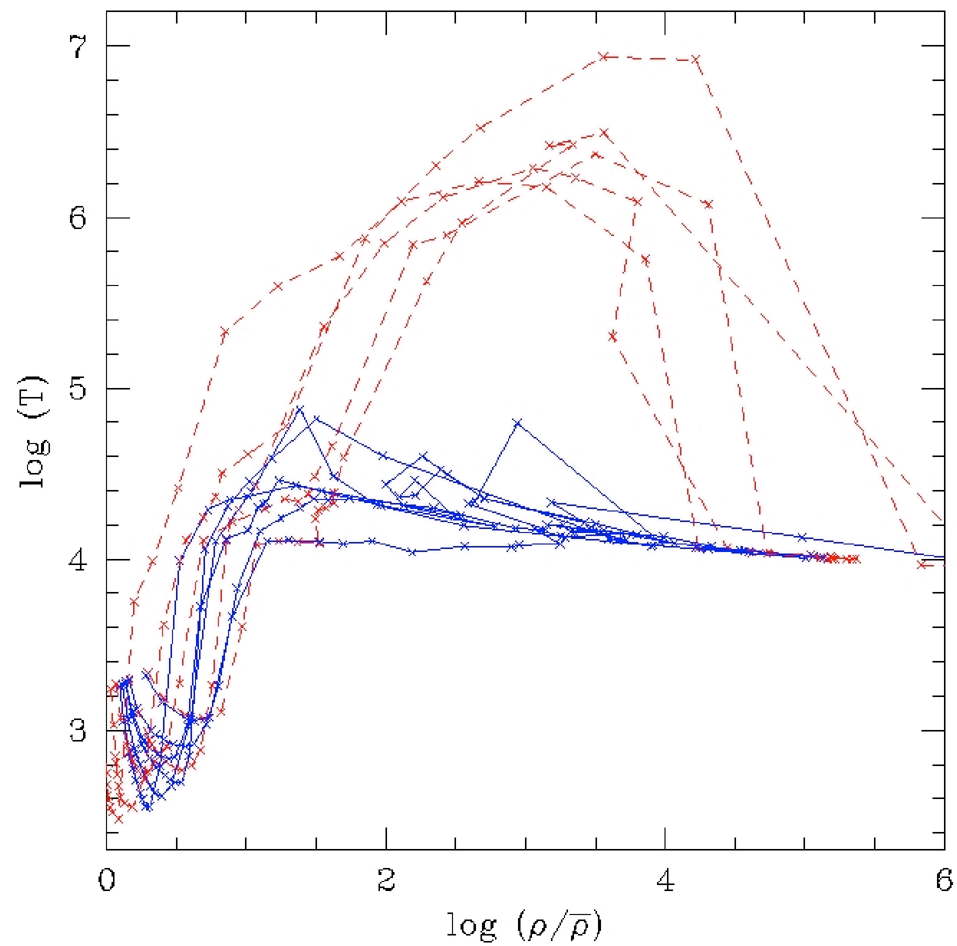
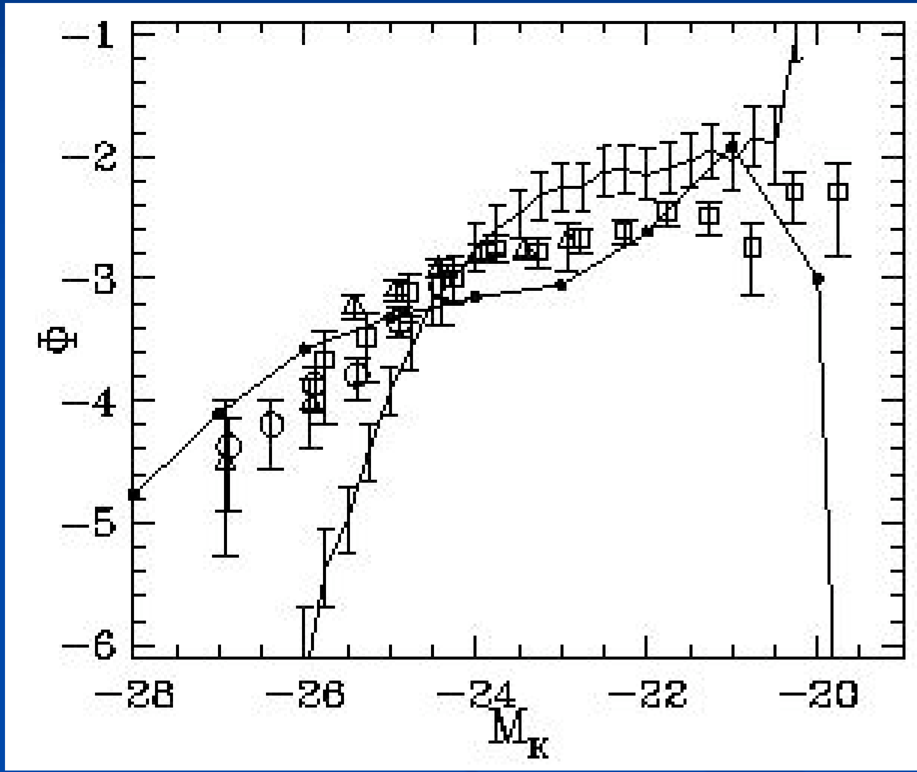


Fig. 18. The evolutionary trajectories in $\rho - T$ space of randomly selected hot (dashed lines) and cold (solid lines) mode particles that are accreted at $z = 3$. For cold mode we use $T_{max} < 100000$K and for hot mode $T_{max} > 1,000,000$K.

Bright-end Excess in NIR LF

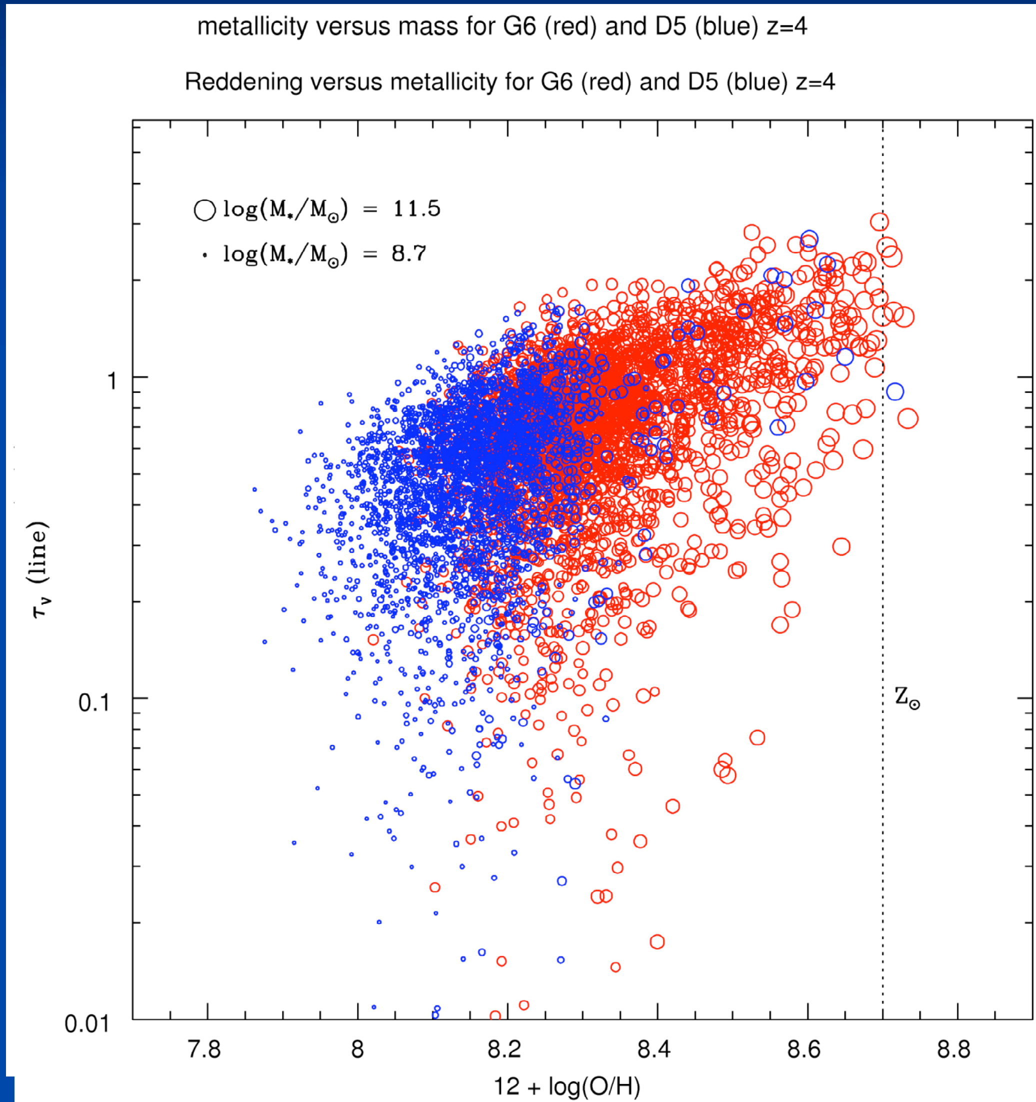
- Excess evident at z~0 (vs. 2MASS), but not so evident vs. K20 data at z=0.5_1.5.
- Simulated K-band LF bright end doesn't evolve much from z=2_0, while data shows substantial passive evolution.
- Simulation evolution a balance between new stars forming and old stars fading, plus lots of dry merging.
- What stops growth? (AGN? Superwinds?) Does dry merging occur or is it numerical overmerging?



Squares, triangles, diamonds: G6 simulation results at z=0, 1, 2.
Line with errorbars: 2MASS @ z~0
Line with circles: K20 @ z~1.

Simulating Dust Extinction

- "Fiducial" Dust Model: Calzetti Law. Take z~0 Z-τ_V relation from Tremonti et al, plug in stellar metallicities from simulation, plus Gaussian scatter to broadly match data.
- Big galaxies are more metal-rich, dustier. Most galaxies have Z~0.1-1 solar.
- Compared with HDFN extinctions measured by Thompson (2003), with broad agreement.



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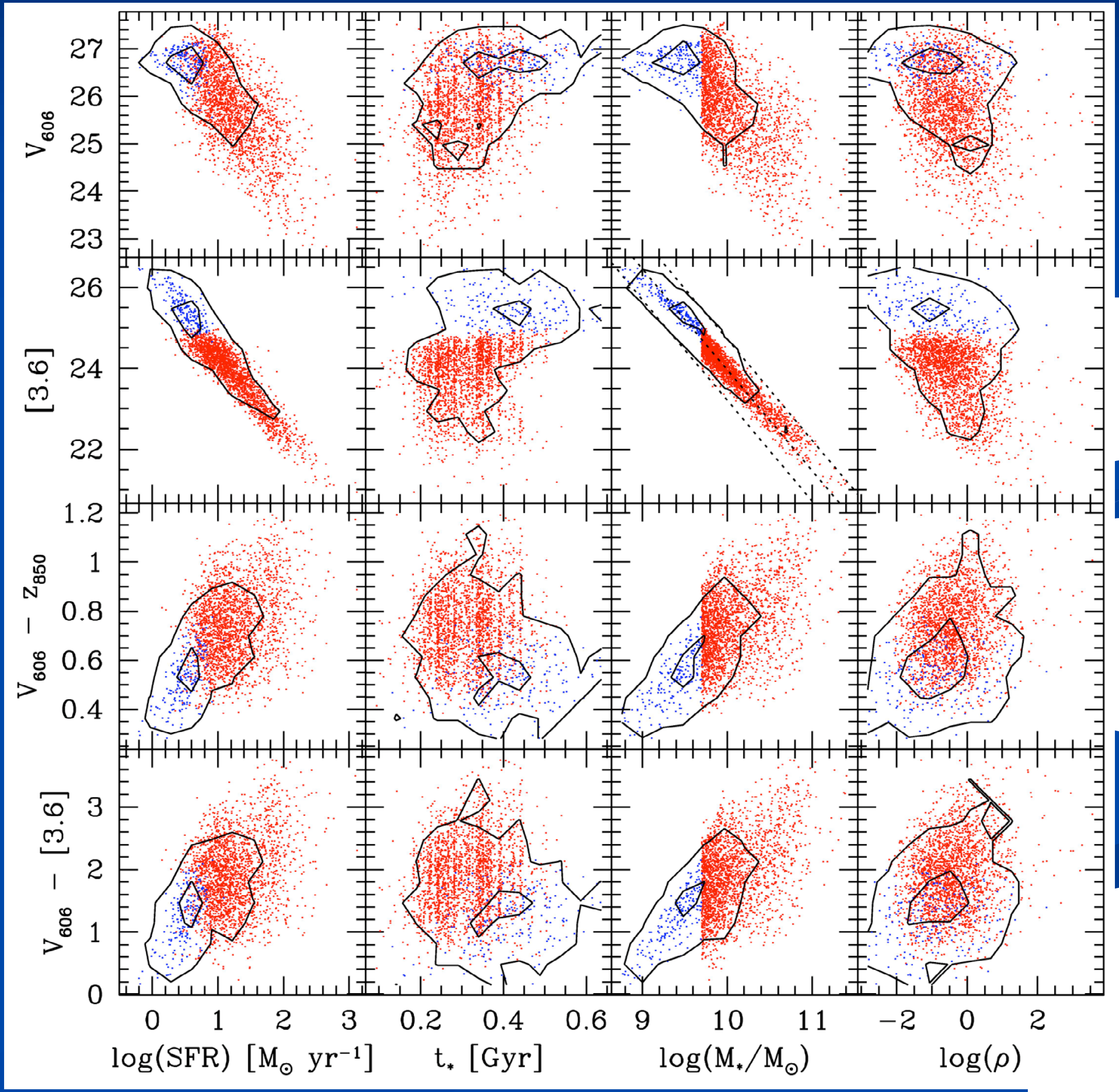
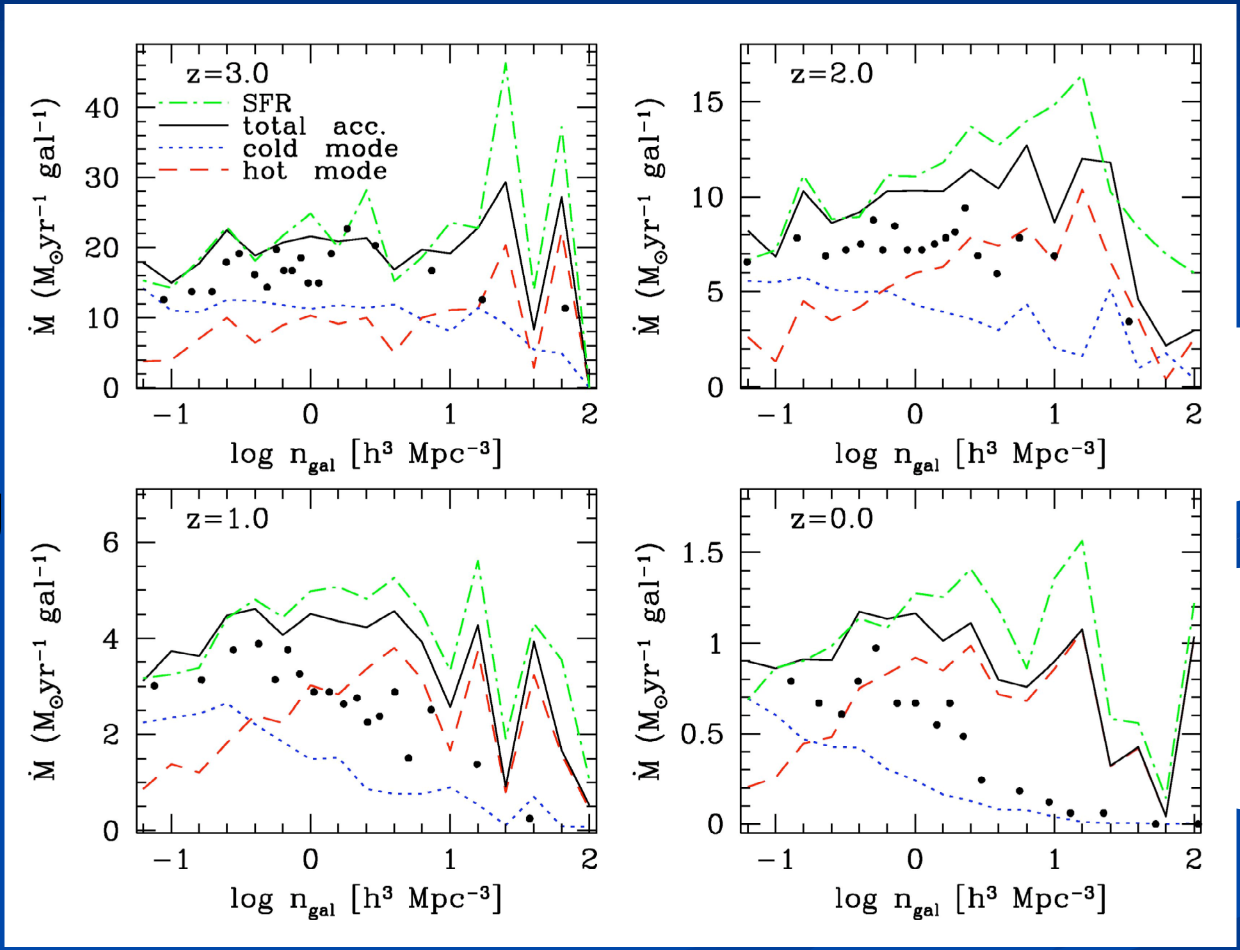
Physical Properties of Simulated GOODS Galaxies

- Simulations: High-z UV-drop galaxies are generally most massive, strongest star formers (not transient bursts).
- Couple of galaxies with SFR>1000 $M_\odot$/yr: SCUBA sources?
- Big galaxies are redder, mostly due to higher Z ⇒ more dust. Birthrates ~ constant.
- M/L lines: 1/8, _, and _, showing typical



Accretion vs. Environment

- At high-z, specific accretion rate doesn't depend depend much on environment (local galaxy density).
- At low-z, fairly strong trend with galaxies >few L* density showing much less accretion (compares well to SDSS, Gomez etal 03)
- Hot mode also is dominant in higher density regions, tracing mass dependence



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Points: Median accretion ra